Ultrahigh-frame-rate OH fluorescence imaging in turbulent flames using a burst-mode optical parametric oscillator

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Burst-mode planar laser-induced fluorescence (PLIF) imaging of the OH radical is demonstrated in laminar and turbulent hydrogen–air diffusion flames with pulse repetition rates up to 50 kHz. Nearly 1 mJ/pulse at 313.526 nm is used to probe the OH $P_2(10)$ rotational transition in the (0,0) band of the A-X system. The UV radiation is generated by a high-speed-tunable, injection-seeded optical parametric oscillator pumped by a frequency-doubled megahertz-rate burst-mode Nd:YAG laser. Preliminary kilohertz-rate wavelength scanning of the temperature-broadened OH transition during PLIF imaging is also presented for the first time (to our knowledge), and possible strategies for spatiotemporally resolved planar OH spectroscopy are discussed. © 2009 Optical Society of America

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The OH radical is an important marker of high-temperature reaction zones in turbulent combustors. Owing to the unsteady nature of turbulent flames, high spatiotemporal resolution is necessary for a better understanding of species transport and flame chemistry, as well as for model validation. To date, OH planar laser-induced fluorescence (PLIF) is limited to ~5 kHz recorded continuously or ~10 kHz for up to eight sequential images [1–3]. Higher frame rates and sequence lengths are required to capture high-speed unsteady turbulent phenomena with a wide range of time scales. Application of high-speed OH PLIF to turbulent jet flames, swirl-stabilized combustors, and pulsed combustors offers the potential for increased understanding of local flame extinction, combustion instabilities, and production of pollutants. In the current study, we report the use of a UV spectroscopic system that can produce bursts of high-power tunable laser light at repetition rates of tens of kilohertz with significantly longer time sequences than previously reported.

The laser system is comprised of a high-speed-tunable, injection-seeded optical parametric oscillator (OPO) pumped by a frequency-doubled megahertz-rate burst-mode Nd:YAG laser, as shown in Fig. 1. Although the custom OPO is new to this work, the burst-mode Nd:YAG pump laser is the same as that presented by Jiang *et al.* [4] and will be only briefly described here. Up to 1.2 J per burst at 532 nm is generated by the pump laser with pulse-repetition rates of 25 to 50 kHz and linewidths of less than 0.004 cm^{-1} FWHM. The design of pump laser is described in detail in [4]. The OPO is comprised of two phase-matched beta-barium borate (BBO) crystals (CASTECH $\theta = 22.4°$) inside a linear cavity with a 20% reflective output coupler for signal generation at 763 nm. A tunable distributed-feedback (DFB) diode laser (Toptica DL100) with a linewidth of 0.014 cm^{-1} FWHM is used to injection seed the cavity through an optical isolator at the signal wavelength. With a pump-beam diameter of about 3 mm, the OPO signal energy is ~100 mJ per burst, yielding an OPO conversion efficiency of 8.5%. The output signal is sum-frequency mixed with the residual 532 nm pump beam in a BBO crystal (CASTECH $\theta = 40.9°$) to produce ~15 mJ per burst of narrow-linewidth 313.526 nm UV radiation with a divergence of 1.4 mrad and an M^2 factor of 8.5. The UV radiation then passes through a 1000 mm focal-length spherical focusing lens and a −25 mm focal-length cylindrical lens to produce an ~1-mm-thick sheet with a height of ~50 mm at the probe volume. The OPO out-

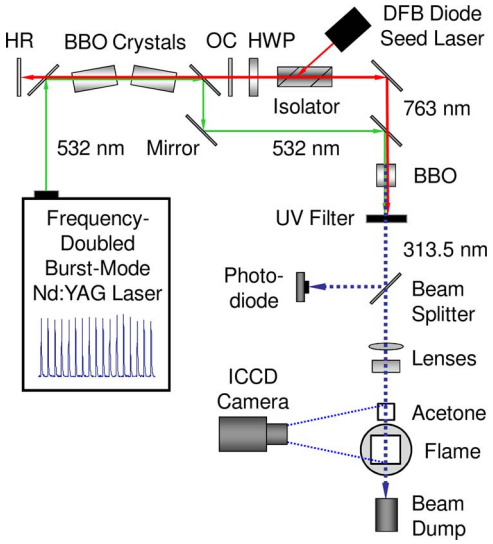

Fig. 1. (Color online) Diagram of a high-speed OH PLIF imaging system: HR, high reflector; OC, output coupler; HWP, half-wave plate.

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put is tuned to the $P_2(10)$ rotational transition of OH in the (0,0) vibrational band of the A-X electronic system, which has a weak temperature dependence in the 1500–2500 K range [5].

A Princeton Instruments ultra-high-speed intensified CCD (ICCD) camera oriented perpendicular to the laser sheet is used to acquire sequences of up to 28 OH PLIF images. This limits the number of images in the burst sequence, although high-speed-camera technology is continuously improving and sequences of up to 100 images are currently available. The PLIF signal is collected utilizing a Nikkor $f/4.5$ UV lens with a magnification factor of 5. Each image is exposed for 300 ns to eliminate flame emission, and the intensifier gain is set to less than half of the full range for the reported conditions.

A steady-state, laminar, near-adiabatic flame stabilized over a Hencken burner was used to characterize the performance of the high-speed OH PLIF system. The equivalence ratio (Φ), defined as the fuel-air ratio divided by the stoichiometric fuel-air ratio, was varied from 0.5 to 1.3. The fuel and the air were fed separately through a honeycomb mesh 25.4 mm $\times$25.4 mm in size. Hydrogen and air flow rates were controlled by mass-flow controllers with ±2% accuracy such that the total flow rate of the products was constant at 60 standard liters per minute (slpm) for all conditions, yielding an approximate flow velocity of 2 m/s. A nitrogen coflow of 15 slpm (0.4 m/s) was used to minimize ambient disturbances.

The UV laser energy was found to vary from shot to shot, causing fluctuations in the OH PLIF signal on the order of 21% rms over an entire burst sequence. These fluctuations are most likely due to variations in the pump-laser energy and the effect of subsequent nonlinear frequency-conversion processes during UV generation. In addition, significant laser-intensity variations were observed along the height of the laser sheet. As a result, a quartz cuvette filled with acetone vapor was placed in the viewing area to track laser intensity variations in time and space for image normalization on a shot-to-shot basis. As shown in Fig. 2, normalization using spatially integrated acetone fluorescence reduced energy fluctuations during 50 kHz pulse trains from 21% to 11% of the mean value. This is of the same order as the uncertainty in local PLIF-signal intensities owing to collisional-quenching effects. Corrections to the beam profile for 50 kHz pulse trains, shown in Fig. 3, reduce spatial intensity variations from 50% to 10% of the mean value. With this correction, it is possible to detect the slight drop in OH concentration higher in the product stream, as expected. These procedures show that reasonable accuracy in spatiotemporal OH PLIF measurements can be achieved with the current system.

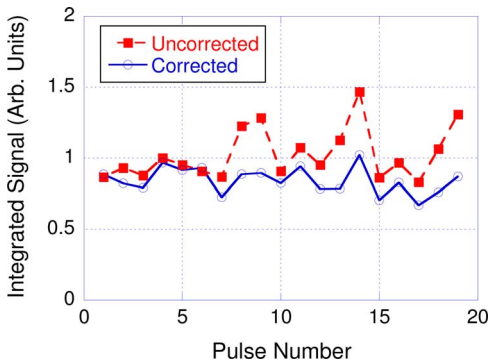

Fig. 2. (Color online) Corrected and uncorrected OH-fluorescence intensity from a 50 kHz burst.

In addition to the steady-state laminar flame, the high-speed OH PLIF system was evaluated with a laboratory-scale sonic hydrogen–air diffusion flame stabilized over a 1 mm diameter orifice at atmospheric pressure. A burst-mode repetition rate of 25 kHz was sufficient to capture the transient combustion phenomena, although 50 kHz performance was also achieved. Figure 4 shows a partial series of high-speed OH PLIF images obtained 50 jet diameters from the nozzle in a 4.5 cm $\times$ 4.5 cm region. The time evolution of various flame structures can be tracked in the image sequence, with turbulent eddies along the interface influencing the mixing process and local combustion chemistry. For example, the evolution of a flame layer is marked with a white circle in Fig. 4 as it is pinched off from the main reaction zone and subsequently extinguished. These results illustrate the ability of the current system to track turbulent flame phenomena through the relevant times scales of fluid–flame interaction. Such data can be used to provide a phenomenological description of high-speed turbulent combustion and improved understanding of practical combustors for model development and validation.

As noted earlier, another new feature of the custom-built burst-mode OPO demonstrated in this Letter is the ability to tune the seed laser during a burst sequence. Frequency tuning of 20 GHz can be achieved at rates up to 10 kHz for the current system, potentially enabling high-speed planar spectroscopy of temperature-broadened molecular transitions for the first time (to our knowledge). Tests were performed in the same steady flame described previously to determine the potential for scanning the wavelength of the UV radiation during a burst. The injection current of the seed laser was modulated by a ramp waveform provided by an arbitrary waveform generator with a frequency of 2.5 kHz, leading to a 20 GHz variation in UV wavelength from the OPO. The temperature-broadened linewidth of the OH $P_2(10)$ transition is ~9 GHz FWHM and therefore within the scanning capability of the spectroscopic system. A 2 GHz free spectral range etalon (Burleigh)

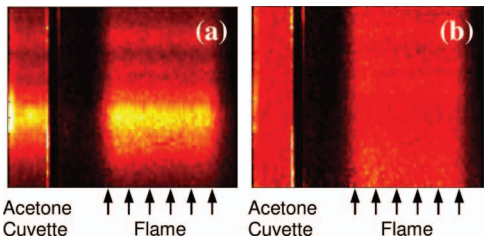

Fig. 3. Instantaneous images of OH PLIF from a 50 kHz burst in a Hencken flame (a) before and (b) after normalization for spatial laser-intensity variations.

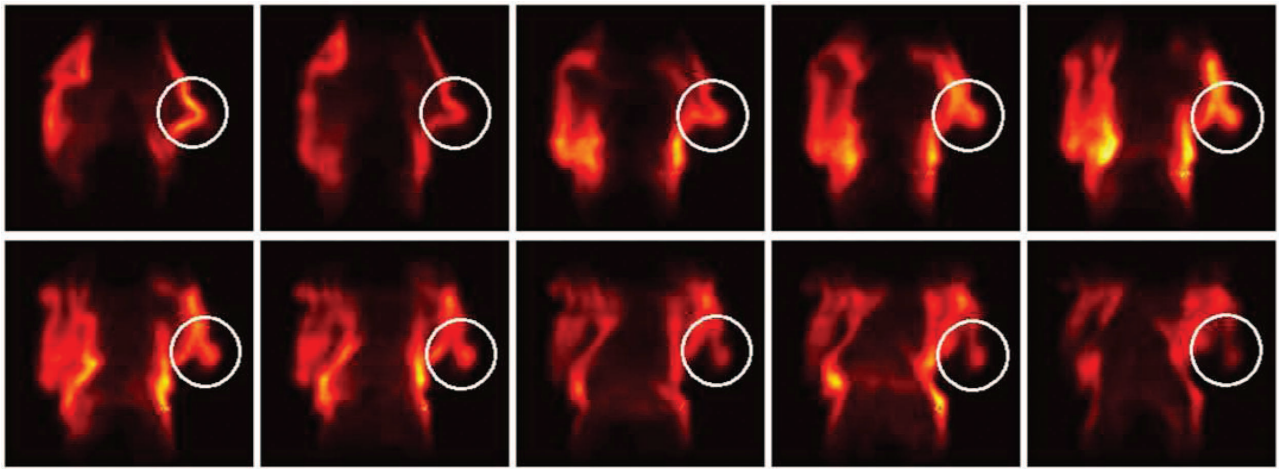

Fig. 4. Partial OH PLIF image sequence from atmospheric-pressure turbulent H_2-air diffusion flame showing OH layer evolution and extinction caused by turbulence–flame interactions.

was used to determine the instantaneous frequency of the seed beam and facilitate a time- to frequency-domain conversion for the recorded OH PLIF images. Figure 5 shows the OH PLIF signal during a wavelength scan across the $P_2(10)$ transition collected in a steady Hencken burner at $\Phi = 1.0$. The poor fit with the theoretical OH line shape in the center of the Voigt profile (computed assuming equilibrium flame temperature) cannot be attributed to laser intensity fluctuations, as these are significantly reduced by the shot-to-shot normalization procedure (see Fig. 2). The DFB laser intensity of ~1 mW is also much higher than the threshold required for seeding (measured at several microwatts), ensuring sufficient energy during diode-current tuning. However, as the seed laser is tuned on and off the resonant cavity modes of the OPO, the output bandwidth varies less than 0.018 cm^{-1} to ~34cm^{-1}, respectively, measured using a linewidth meter with 0.004 cm^{-1} resolution (HighFinesse) and a 1.26 m spectrometer. This change in bandwidth affects the overlap with the OH transition and cannot be normalized through fluorescence of acetone, which has a broad absorption spectrum. The effects of mismatch between cavity modes and seeder

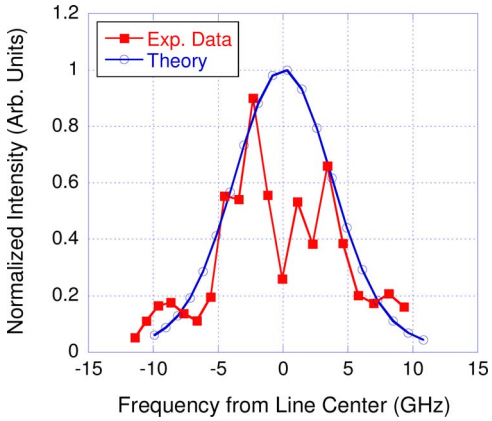

Fig. 5. (Color online) OH PLIF signal during wavelength scanning compared with theoretical Voigt profile.

wavelength can be addressed in several ways, including active cavity stabilization using a piezoactuated high reflector or minimization of the effect using cavity misalignment [6]. The reasonable measurement of OH linewidth in Fig. 5, however, indicates that it is possible resolve molecular transitions within an image sequence.

In conclusion, we have characterized an ultra-high-frame-rate OH PLIF imaging system utilizing an injection-seeded burst-mode OPO. Corrections for spatiotemporal laser intensity variations were demonstrated in a steady calibration flame, and OH PLIF at speeds up to 50 kHz were demonstrated in a turbulent hydrogen–air diffusion flame. Furthermore, we have evaluated the feasibility of rapidly tuning the OPO over a molecular transition and analyzed the effects of cavity modes on seeding stability.

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